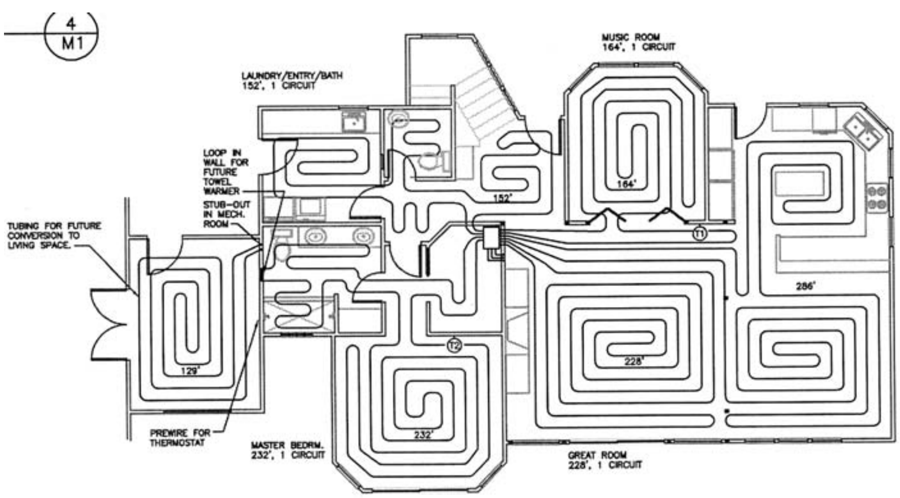
CALIFORNIA ENERGY COMMISSION

Final Report Compilation for

Residential Hydronic Radiant Cooling and Heating Assessment



TECHNICAL REPORT

October 2003
P-500-03-096-A14

Gray Davis, *Governor*

CALIFORNIA ENERGY COMMISSION

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Acknowledgements

Evelyn Baskin with Oak Ridge National Laboratory was the principal investigator. David Springer and Marc Hoeschle with Davis Energy Group provided instrumentation installation and monitoring services.

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Program's final report and its attachments are intended to provide a complete record of the objectives, methods, findings and accomplishments of the Energy Efficient and Affordable Commercial and Residential Buildings Program. This attachment is a compilation of reports from Project 4.3, *Residential Hydronic Radiant Cooling and Heating Assessment*, providing supplemental information to the final report (Commission publication #P500-03-096). The reports, and particularly the attachments, are highly applicable to architects, designers, contractors, building owners and operators, manufacturers, researchers, and the energy efficiency community.

This document is one of 17 technical attachments to the final report, consolidating two research reports from Project 4.3:

- *Monitoring Plan, Springer Residence* (May 2002)
- *Final Report, Residential Hydronic Radiant Cooling and Heating Assessment* (Sep 2003)

The Buildings Program Area within the Public Interest Energy Research (PIER) Program produced this document as part of a multi-project programmatic contract (#400-99-011). The Buildings Program includes new and existing buildings in both the residential and the nonresidential sectors. The program seeks to decrease building energy use through research that will develop or improve energy-efficient technologies, strategies, tools, and building performance evaluation methods.

For the final report, other attachments or reports produced within this contract, or to obtain more information on the PIER Program, please visit www.energy.ca.gov/pier/buildings or contact the Commission's Publications Unit at 916-654-5200. The reports and attachments, as well as the individual research reports, are also available at www.archenergy.com.

Abstract

Project 4.3, ***Residential Hydronic Radiant Cooling and Heating Assessment,***

Project 4.3 compared the performance of different modes of cooling and heating in a single residence. The house is equipped with an innovative HVAC system which includes a conventional forced air ductwork system, a variable speed air handler with a hydronic coil and an outside air economizer, and a slab-embedded hydronic radiant system. A small DX chiller supplies mechanical cooling and a condensing water heater is used in heating mode. Three cooling modes were tested: (1) conventional air distribution, (2) conventional air distribution augmented by hydronic pre-cooling of the slab at night, and (3) conventional air distribution augmented by pre-cooling the building mass using outside air at night and hydronic slab pre-cooling if necessary.

- The radiant hydronic cooling was effective in shifting some of the cooling load into off-peak hours and greatly reduced energy use.

- Using night ventilation in conjunction with hydronic radiant pre-cooling was even more effective at shifting load into off-peak hours.

This document is a compilation of two technical reports from the research.

DAVIS ENERGY GROUP

Springer Residence
(Winters, CA)
Monitoring Plan
AEC PIER Project

Report Issued: **May 24, 2002**

Presented To: **Vern Smith, AEC**
Evelyn Baskin, ORNL

Prepared By: **Davis Energy Group, Inc.**
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1 BACKGROUND & OBJECTIVES

The goal of this monitoring project is to provide detailed monitoring data to Architectural Energy Corporation (AEC) and Oak Ridge National Laboratory (ORNL) on the heating and cooling system performance of an advanced house located in Winters, California (approximately 40 miles west of Sacramento). AEC and ORNL are interested in gathering data on the HVAC distribution efficiency and indoor comfort characteristics of advanced HVAC systems and distribution technologies. The Winters house, owned by Davis Energy Group president David Springer, includes both radiant and forced air heating and cooling delivery, as well as night ventilation cooling, and therefore provides an excellent opportunity to evaluate these features individually and in combination for their energy savings and peak load shifting benefits.

The HVAC system includes the following:

- Forced air heating distribution to all major rooms
- Radiant heating distribution to all first floor rooms
- Radiant cooling distribution to the main living areas only (Great Room, Dining Room, Kitchen, Entry, Laundry, ½ Bath).
- A high-capacity condensing water heater for heating domestic hot water and for space heating (radiant and/or forced air distribution).
- A hot/chilled water air handler with variable speed (GE ECM-powered) fan.
- A split-system cooling system with the condensing unit supplying a refrigerant-to-water heat exchanger capable of delivering chilled water to radiant floor tubing or to the hydronic fan coil.
- A "NightBreeze" control system and damper which provides summer ventilation cooling using the air handler fan and winter fresh air ventilation.

The specific monitoring objectives are to gather detailed monitoring data to allow ORNL to assess comfort, energy, and demand characteristics of various HVAC system operating modes. The collected data will allow energy use and peak demand comparisons; for ASHRAE-defined comfort calculations using indoor air, air velocity, and mean radiant temperatures; and radiant vs. forced air distribution efficiency comparisons using ASHRAE 152P. The monitoring will continue for one year with a projected start date of June 15, 2002.

The system will be operated in three modes during the cooling season, each lasting for approximately one-month. The three modes are as follows:

1. Conventional cooling mode: Uses the condensing unit, air handler, and forced-air distribution to meet cooling loads in response to an 80°F thermostat setting (upstairs thermostat location).
2. Slab pre-cooling: Applies conventional cooling, plus chilled water cooling of the living area concrete floor for the purpose of shifting peak air conditioning load. Floor

cooling will operate between 4 AM and 8 AM. The floor cooling air temperature setpoint will be 70°F during this period. Conventional cooling will operate to maintain second floor temperatures at an 80°F setpoint.

3. Slab pre-cooling and night ventilation cooling: The existing NightBreeze controls will operate the air handler fan and outside air damper to ventilate the house with cooler outside air when conditions permit. If the ventilation system fails to lower the indoor air temperature to 70°F by 4 AM, the condensing unit will operate to cool the floor as in Mode 2.

The owners may use natural ventilation (open windows) during any of these test periods, and will maintain a log of which windows are operated and on what schedule.

The system will be operated in two modes during the heating season to assess the relative distribution efficiencies of radiant floor heating and forced air hydronic heating. A minimum six weeks of monitoring will occur in each mode, centered around the middle of winter (January 7th). Radiant heating will be operated initially so that the slab temperature will not need to be raised significantly at the mid-winter mode change[1].

The Winters house is currently being monitored on a reduced scale to gather data on the performance of the NightBreeze system. The proposed monitoring will require the existing DT-50 datalogger to be replaced by a DT-500 logger which has more input channels.

2 MONITORING STRATEGY

2.1 Key Monitoring Parameters

Key parameters required for evaluating impacts and verifying operation include:

- Total house space conditioning load (heating and cooling)
- Ventilation system cooling output
- Air conditioning system cooling output
- Fan and pump electrical energy use
- Condensing unit energy use
- Outdoor and indoor temperatures and relative humidity
- System status

Specific monitoring data points necessary to define the key parameters include:

[1] In the analysis of the data, the first week or more of forced air heating data should be discarded so that residual slab heat is not credited to forced air system heat delivery or reduced envelope load.

Temperature: Supply and return air; indoor and outdoor air; immersion temperatures on hydronic supply and return lines

Relative humidity: Outdoor, indoor, and supply/return RH on the fan coil unit

Insolation: Solar insolation measured by a pyranometer.

System Status: The status of the relief dampers and hydronic heating pumps

Airflow: An airflow vs. power curve will be generated for the variable speed air delivery system. A powered flow hood or True Flow airflow measuring grid will measure airflow coincident with blower power measurements.

Water Flow: supply or return flow into the hydronic delivery system will be measured.

Electrical Energy: Condensing unit, fan coil blower motor, pump power (or one-time measurement of hydronic pump power and status monitoring)

Gas Use: Gas consumption for instantaneous water heater

Fan RPM: Motor RPM will be used to calculate airflow rates from fan test data provided by the equipment manufacturer

2.2 Data Acquisition Approach

Individual monitoring systems will be installed to obtain, store, and transfer data. Monitoring systems will consist of dataloggers, multiple sensors, and a modem for communicating data via phone lines. Other test equipment will be used for one-time measurements. Monitoring and test equipment in general include:

- Dataloggers for temperature, power, water flow and insolation measurement
- Solid state or RTD temperature sensors for indoor, outdoor, and duct temperatures
- Immersion thermocouples for water temperatures
- 24V relays for status monitoring of pumps and damper position
- True RMS power monitors for blower fan, pumps, and condenser energy use
- Powered flow hood or True Flow grid for airflow vs. power and RPM calibration measurement

All datalogger sensors will be scanned every 15 seconds, and data will be summed or averaged (as appropriate) and stored in datalogger memory every 15 minutes. The dataloggers will also compute energy transfers at 15 second intervals by multiplying flow rates by temperature differences.

Datalogger memory will be sufficient to store at least four days of data, so that loss of communications will not interrupt the stream of data. Dataloggers will be powered by low voltage power supplies with battery backup to protect against data loss during power outages.

Data, in comma-delimited ASCII format, will be regularly downloaded to a central computer and screened using software to review data ranges. Out-of-range data will be reported and investigated to determine whether a sensor or monitoring error exists or equipment has failed. Data will be transferred to ORNL and AEC on a monthly basis in comma-delimited ASCII format.

2.3 Monitoring Period

The project schedule provides for installation of monitoring equipment by June 15, 2002. Formal monitoring will commence when the monitoring system has been commissioned and calibrated, and will continue for at least twelve months, terminating not later than July 2003. Dates for monitoring the various operating modes are as follows:

Operating Mode	Schedule
Standard Air Conditioning	June 15 – July 15
Air Conditioning with Slab Pre-cooling	July 16 – August 15
A/C, Slab Pre-cooling & Night Ventilation	August 16 – September 15

3 MONITORING SYSTEM DESIGN

3.1 Datapoints

Datapoints are defined in detail in the attachments. Dataloggers will be used to calculate certain values from inputs. Calculated values related to the HVAC system including space heating and cooling energy, ventilation cooling energy (including economizer cycle[2]), and fresh air vent winter heating load. Since both heating and cooling energy are measured using a water flow meter and supply-return temperature sensors, total (sensible and latent) cooling loads will be captured.

-here-

3.2 Datalogger Specifications

Table 1 lists datalogger channel requirements, and channel specifications for the Data Electronics DT-500 proposed to be used for this project. Analog inputs are single-ended (referenced to ground). Digital channels will be used for power monitors and signal states; high-speed counter inputs will be used with fluid flow meters and to determine fan speed on the variable speed blower units. Detailed datalogger specifications are provided in the attachments.

Table 1: Datalogger Channel Requirements and Input Specifications

	Analog	Digital	Counter
Channels Required	21	4	2

[2] If outdoor air is cooler than indoor air and the air conditioner is operating, the outside air damper will open.

Datataker 500	30	4	3

3.3 Sensor Types and Specifications

Table 2 lists the types of sensors to be used for the various monitoring points and their performance specifications. Sensor selection was based on functionality, accuracy, cost, reliability, and durability. Specific model numbers are listed as examples; similar models by other manufacturers may be used based on price and availability. Signal ranges for temperature sensors correspond approximately to listed spans. Detailed manufacturers' specifications are provided in the attachments.

Table 2: Sensor Specifications

Type	Application	Mfg/Model	Signal	Span	Accuracy
LM34	indoor temp.	Basys TS 1100	~0-2 V	.01V per °F	±1% (70°F)
RTD	outdoor temp.	RM Young 41342LF	4-20 mA	-30 - 130°F	±1.6%
RTD	duct temp.	ACI TTM 100-7-D	4-20 mA	40 - 130°F	±1.5%
Flow meter	water flow	Onicon F1300	0-15Vpulse	~800 pulse/gal	±2%
Gas meter	WH gas use	Equimeter S-275P	pulse	1 pulse/ft^3	±2%
Type T	water temp.	Gordon 20CTOUH	~0-3 mV	~0-160°F	±0.4%
Type T	Globe temp*	Thermocouple wire	~0-3 mV	~0-160°F	±0.4%
power monitor	elect. energy	CSS-WNA-1P-240-P	pulse	4 pulse/Wh	±0.5%
24V Relay	signal state		digital		

"*" the thermocouple will be located within a flat-black painted ping pong ball

3.4. Equipment Panel

Dataloggers with batteries, terminal strips, and electrical power strips will be mounted in a locking metal enclosure. The enclosure will also contain pre-wired terminals for connection to powered sensors and for 4-20 mA signal inputs. Shunt resistors for converting 4-20mA to 0.4 to 2.0 VDC will be pre-wired.

3.5. Wiring

Wiring shall be Belden 22 gauge shielded communications cable or equal, #8761 single pair, #8771 3-conductor, and #8723 two pair. Thermocouple wire shall be Gordon T20-5-510 or equal.

4 MONITORING SYSTEM INSTALLATION

4.1 Documentation

Monitoring documentation, included in the attachments, includes the following:

- Datapoint list
- Drawings showing sensor locations

- Datalogger and sensor wiring diagrams and cable schedules

Any changes to the monitoring plan made in the field will be noted in the documentation. Calibration data such as flowmeter meter calibration factors will be recorded, as well as datalogger serial numbers.

4.2 Datalogger Installation

The monitoring panel containing the dataloggers and other equipment will be installed in the attic mechanical area. Power connections will be secured and/or labeled to prevent inadvertent disconnection. Equipment panel covers will be marked with a contact name and phone number.

4.3 Sensor and Wiring Installation

Sensors and wiring will be securely installed, but in a manner as to minimize damage to existing surfaces/materials and reduce repairs needed during decommissioning. Wiring will be labeled at both ends using abbreviations listed in the cable list. Except for equipment located in close proximity to the monitoring panel, wiring will be installed in walls and attic prior to drywall application.

The following procedures will be followed for installation of the various sensor types:

Indoor Temperature Sensor. If a thermostat is installed in that room, the indoor sensor will be installed in close proximity.

Floor Surface Sensor. Surface mount thermocouples will be installed in uncarpeted locations to measure hard surface floor temperature. Sensor locations will be in an area not subject to traffic or disturbance.

Globe Temperature Sensor. Thermocouples will be inserted into ping pong balls (painted flat black) and suspended from the ceiling or wall, as appropriate.

Outdoor Temperature and Relative Humidity Sensor. Install in shielded enclosure (Gill radiation shield) with no direct solar exposure.

Supply and Return Air Temperature and Relative Humidity Sensors. Sensors will be mounted in supply and return plenums of the indoor unit. Supply sensors will be located as far from heating/cooling coils as possible, but prior to any duct branches. Sensor boxes will be secured using sheet metal screws.

Power Monitors. Verify that power is disconnected during power monitor installation. Install current transformers (CTs) with proper orientation to line and load, and connect to power monitors in accordance with manufacturers instructions. Locate power monitors close to CTs, preferably inside equipment. If exposed, mount power monitor boxes using sheet metal screws or double-stick tape. Observe that CTs and power monitors do not present an electrical hazard.

Flow meters. In-line flow meters will be installed into copper pipe in the locations shown on the sensor plan. Where possible, the will be installed no closer than 10 pipe diameters from the nearest upstream elbow.

Air Velocity Sensors. Locate in room where the sensor is not obstructed from typical airflow circulation. Avoid placing behind plants or in a corner.

Wiring. Wiring will be routed as inconspicuously as possible between the datalogger and sensors. Wiring will be labeled at both ends with the sensor abbreviation. Wiring in framing and attic will be secured with staples and routed so as to minimize risk of damage during construction. Wiring exposed to view will be run in conduit or neatly bundled and secured to the wall using plastic wire tie anchors. Strain relief will be provided at points of connection, including the monitoring panel.

4.4 Commissioning and Calibration

A commissioning log will be completed to record sensor calibrations, one-time measurements, and other data. On completion of equipment installation, a laptop computer will be connected to the datalogger for reading real time data, and the following calibrations and verifications will be completed:

Air Temperature. Using calibrated temperature sensor, record monitored and calibrated temperatures for each sensor. Duct sensors may be removed, or calibrated prior to mounting in ducts.

Relative Humidity. Using calibrated handheld RH sensor, record monitored and calibrated temperatures for each RH sensor.

Power. Activate monitored system and verify power measurement. Reverse polarity of CT, voltage, and datalogger connections as needed to correct for lack of readings.

Airflow. Set up the datalogger to record fan RPM and use a TrueFlow (Energy Conservancy) air handler flow meter to measure system airflow. Record airflow rates and RPM at control settings of 200-1600 CFM in increments of 200. A fit of these data will be used to program the datalogger to compute airflow from RPM.

Water Flow. The Onicon flow meters are of high accuracy and come factory calibrated. Each flow meter will be checked to verify the datalogger is recording flow.

Water Temperature Sensors. Operate the system pumps or otherwise initiate flow with the furnace fan off. Immersion thermocouples should indicate comparable supply and return temperatures. Note temperature readings of each sensor and apply an offset, if necessary.

Communications. Dial the datalogger modem from a remote computer and verify communications to both dataloggers.

Permanent Programming. Enter offsets and other program variables determined during commissioning into the site datalogger program, and upload the program. After one day of operation, download and verify all readings.

On completion of commissioning, the site monitoring plan will be updated to document equipment installed, serial numbers, and calibration values.

5 DATALOGGER PROGRAMMING

Dataloggers will be configured with monitoring programs specific to the monitored datapoints. Programs will scan individual channels at 15 second intervals and will store these data in temporary buffers and sum or average the values over a 15 minute logging interval. The 15-second scanning interval provides high data resolution on parameters which may change during the logging interval and allows for more accurate calculation of energy transfers. In addition, the 15-second interval allows for filtering of temperature data to provide representative supply and return water/air temperatures only during system operation.

5.1 Air Side Equations

Equations for calculating energy transfers are very similar, with the exception of the temperatures used. Space heating (or cooling) energy delivered by the hydronic coil will be computed by the datalogger on 15-second intervals, using Equation 1.

Equation 1: Qair = CFM * (Tsupply - Treturn)*1.08

where: CFM = measured airflow for 15-second interval (cubic feet per 15-seconds)
Tsupply = supply air temperature (°F)
Treturn = return air temperature (°F)

If the damper opens to provide fresh air while the heating system is operating, the following equation will be used to calculate space heating energy:

Equation 2: Qair = CFM * (Tsupply - To)*1.08

where: To = outside air

The fresh air vent load will also be calculated for periods when the damper is open to admit fresh air during winter (heating mode) operation, using Equation 3:

Equation 3: Qfavl = CFM * (Trelief - To)*1.08

where, Trelief = relief air temperature (°F)

Equations 4 and 5 will be used for calculating sensible cooling load:

For normal air conditioning operation (damper closed, outside air warmer than inside air):

Equation 4: Qacn = CFM * (Treturn – Tsupply)*1.08

For air conditioning with economizer (damper open, outside air cooler than inside air):

Equation 5: Qace = CFM * (To – Tsupply)*1.08

Equation 6 will be used to calculate the cooling benefit contributed by the economizer (during economizer cycle operation only):

Equation 6: Qacel = CFM * (To – Trelief)*1.08

The following equation will be used to calculate the cooling capacity of the night ventilation cooling system:

Equation 7: Qvc = CFM * (Trelief – To)*1.08

Latent mechanical cooling will be calculated using enthalpy equations from supply and return air temperatures and relative humidity. Depending on datalogger memory available, these calculations will either be completed by the datalogger, or after the data is downloaded.

5.2 Water Side Equations

Heating or cooling delivered from the water heater to the air handler will be computed using Equation 8:

Equation 8: Qhyd = FLH * (TSUP – TRET) * 8.33

Where:	FLH	= hydronic loop flow (gallons)
	TSUP	= supply water temperature to hydronic system (°F)
	TRET	= return water temperature to hydronic system (°F)

Since heat delivered by the air handler is also calculated (Equations 1 & 2), an energy balance can be performed between air and water side heat flows. The sign convention for Equation 8 is "+" for heating and "-" for cooling.

6.0. DATA ACQUISITION

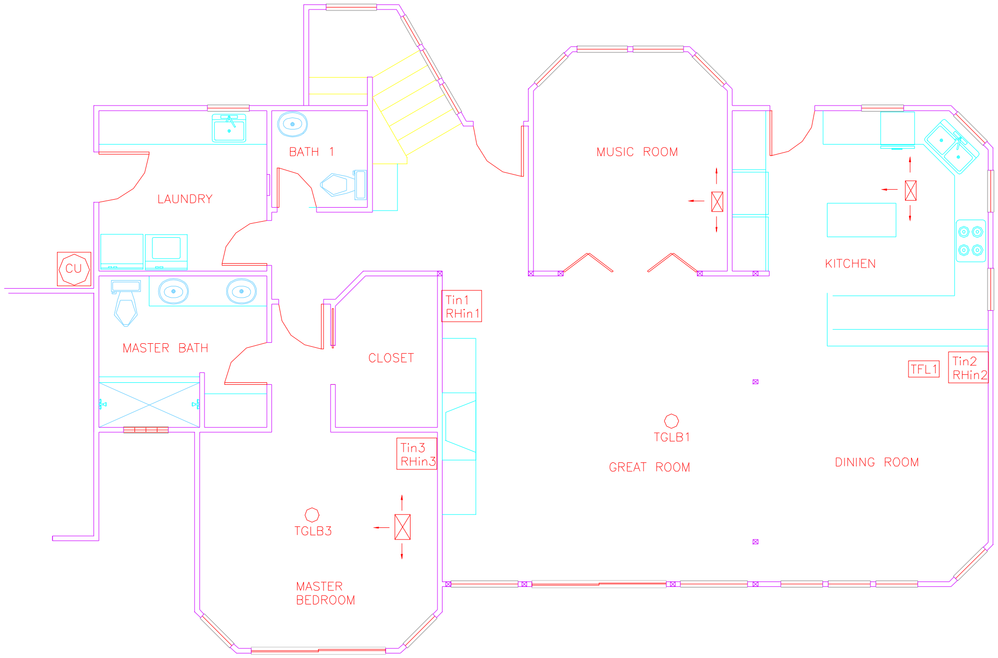
Data will be transferred from the monitoring site to DEG offices using PCMCIA data cards. Data will be transferred at least twice a week. Software will be developed to read in the "raw" data and verify that all readings are within expected values (e.g. indoor air temperature is between 40 and 90°F). An automated screening program scans the data and reports measurements that are out of range. If data are out of range, the suspect data will be visually examined to determine whether a sensor is defective. If the review indicates sensor error a service call will be scheduled to repair or replace sensors. On a weekly basis, data will be graphed in time-series format to further insure the data are physically consistent. For example, if the system is operating in heating mode, supply air temperature and pump energy consumption should both reflect heating operation.

Data will be stored in comma-delimited ASCII format in files named by site and date in the format S#MMYY (where S# is the site number). For example, the July 2002 file for Site 1 would be named "S1010702.DAT". A header list will be developed for use in identifying columnar data for each site. All files will be stored on a DEG computer and files will be archived on a monthly basis and transmitted to both AEC and ORNL.

ATTACHMENTS

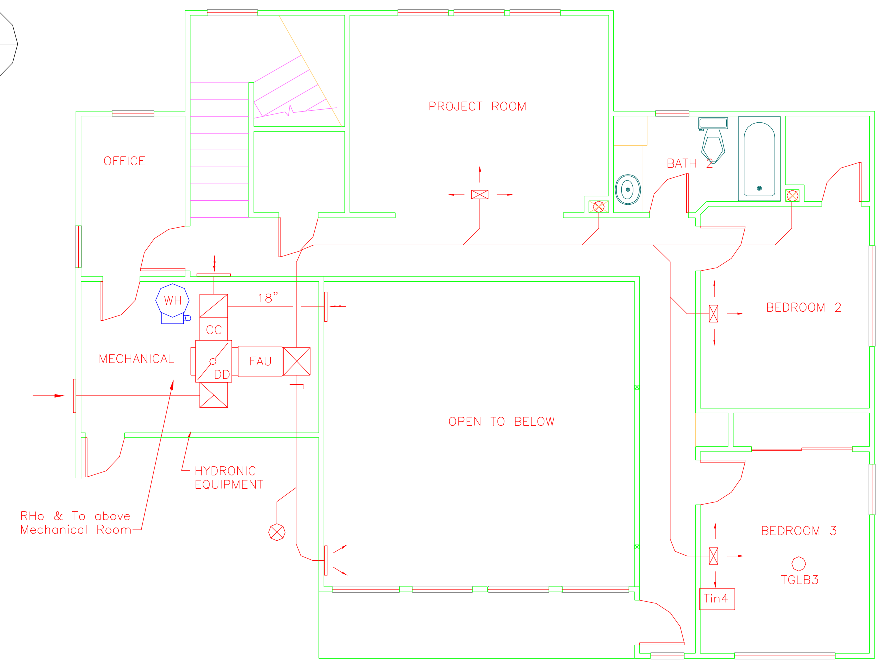
1. Cable List
2. Monitoring Points Plan
3. Mechanical System Monitoring Points

Site:	Z1									
Logger1:	DT-500 Serial No.									
Phone:										
Point		Sensor			Cable				Logger	Logger
No.	Abbrev.	Description	Location	Signal	# Conduct	Color/#	Label	Pair	Channel	Wire
LOGGER #1 (DT-500)										
1	TO	Outdoor temperature	Shielded	RTD, 4-20mA	4	1 (+)	TOUT	b/r	+24V	red
					.	2 (-)			1+	black
2	RHO	Outdoor relative humidity	Shielded	4-20mA	.	1 (+)	TOUT	g/w	+24V	green
					.	2 (-)			1-	white
3	TAS1	Supply air temperature (Unit 1)	FAU	RTD, 4-20mA	4	1 (+)	TAS1/RHS1	b/r	+24V	red
					.	2 (-)			1*	black
4	RHS1	Supply air RH (Unit 1)	FAU	4-20mA	.	1 (+)	TAS1/RHS1	g/w	+24V	green
					.	2 (-)			2+	white
5	TAR1	Relief/Return air temp. (1)	FAU	RTD, 4-20mA	4	1 (+)	TAR1/RHR1	b/r	+24V	red
					.	2 (-)			2-	black
6	RHR1	Relief/Return air RH (1)	FAU	4-20mA	.	1 (+)	TAR1/RHR1	g/w	+24V	green
					.	2 (-)			2*	white
7	TIN1	Indoor temp (great room)		RTD, 4-20mA	4	1 (+)	TIN1/RH1	b/r	+24V	red
					.	2 (-)			3+	black
8	RHIN1	Great room RH		4-20mA	.	1 (+)	TIN1/RH1	g/w	+24V	green
					.	2 (-)			3-	white
9	TIN2	Indoor temp (mstr bedroom)		RTD, 4-20mA	4	1 (+)	TIN2/RH2	b/r	+24V	red
					.	2 (-)			3*	black
10	RHIN2	Master bedroom RH		4-20mA	.	1 (+)	TIN2/RH2	g/w	+24V	green
					.	2 (-)			4+	white
11	TIN3	Indoor temp (dining room)		LM34	3	1 (COM)	TIN3	b/w/r	GND	black
					.	2 (OUT)			4-	white
					.	3 (+7.5)			+24V	red
12	TIN4	Indoor temp (bedroom 3)		LM34	3	1 (COM)	TIN4	b/w/r	GND	black
.					.	2 (OUT)			4*	white
					.	3 (+7.5)			+24V	red
13	TGLB1	Globe temp (great room)		Type T TC	2	1 (+)	TGLB1	blue/red	5+	blue
					.	2 (-)			R	red
						shield			GND	shield
14	TGLB2	Globe temp (mstr bedroom)		Type T TC	2	1 (+)	TGLB2	blue/red	5-	blue
					.	2 (-)			R	red
						shield			GND	shield
15	TGLB4	Globe temp (bedroom 3)		Type T TC	2	1 (+)	TGLB4	blue/red	6+	blue
					.	2 (-)			R	red
						shield			GND	shield
16	THYDS	Hydronic supply water temp		Type T TC	2	1 (+)	THYDS	blue/red	7+	blue
					.	2 (-)			R	red
						shield			GND	shield
17	THYDR	Hydronic return water temp		Type T TC	2	1 (+)	THYDS	blue/red	7-	blue
					.	2 (-)			R	red
						shield			GND	shield
18	DMPS	Damper status	FAU		2	1(+)	DMPS	b/r	7*	red
					.	2(-)			7R	black
19	GAS	Water heater gas use	FAU	Pulse	2	(+)	GAS	b/r	D1	red
					.	(-)			GND	black
20	EAC	Condenser energy		Pulse	2	(+)	EAC	b/r	D2	red
					.	(-)			GND	black
21	EFAN	FAU fan energy	FAU	Pulse	2	(+)	EFAN	b/r	D3	red
					.	(-)			GND	black
22	EPMP	Pump energy		Pulse	.	(+)	EPUMP	b/r	D4	red
					.	(-)			GND	black
23	FLHYD	Hydronic flow		0-15VDC puls	3	(+)	FLHYD	b/w/r	+24V	red
					.	(-)			GND	black
					.	Signal			C1	white
24	FNSPD	Fan speed	FAU	Pulse		(+)	FNSPD	g/w	C2	green
					.	(-)			GND	white



FIRST FLOOR SENSOR PLAN

2
M1



SECOND FLOOR SENSOR PLAN

1
M1

Project 4.3, Residential Radiant Cooling and Heating Assessment

Deliverable 4.3.6a, Final Report

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Prepared for:

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Sacramento, California

March 31, 2003
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Executive Summary

This study was performed in a contemporary house in Winters, California, located approximately 30 miles west of Sacramento. The house had a unique hydronic heating and cooling system which employed a radiant floor slab, a hydronic fan coil unit with a variable speed fan and an outside air economizer, a small chiller, and a condensing gas water heater. The flexible design of the heating/cooling system allowed the house to be operated in different modes, including radiant heating and conventional forced air heating and cooling. The system allowed the floor slab to be cooled by pumping chilled water through the embedded tubing, and also by the use of nighttime ventilation. Because the system was hydronic and was equipped with flow, temperature, and electrical power meters at significant points, it allowed the accurate comparison of energy use when operated in the different modes. Comfort was also measured according to standard techniques developed by the American Society for Heating Refrigeration and Air-conditioning Engineering (ASHRAE). The specific objectives of the project were to compare the electrical demand and energy usage as well as comfort levels in the house when operated in different modes. Three cooling and two heating modes were implemented. They are as follows.

Cooling Modes

1) Mode1: Conventional forced-air to meet cooling loads in response to a thermostat setting
2) Mode 2: Conventional forced-air combined with hydronic slab precooling,
3) Mode 3: Conventional forced-air combined with night ventilation precooling supplemented as needed with hydronic slab precooling.

Heating Modes

1) Mode H1: Hydronic radiant slab heating
2) Mode H2: Hydronic and forced-air heating

The conclusions of the study are as follows.

- Cooling performance results reveal that slab pre-cooling (mode 2) caused some of the energy demand to shift from the on-peak to off-peak hours. This mode also showed the overall lowest energy usage by far, using less than half the energy of modes 1 or 3.
- Slab-cooling with nighttime ventilation (mode 3) shifts the energy demand profile from afternoon to nighttime even more significantly than for mode 2 alone, in part because of the additional building mass which was cooled by nighttime air.
- During heating season, the energy consumption with hydronic forced-air heating (mode H1) was similar compared against hydronic radiant slab (mode H2) heating, with neither mode exerting an advantage over the other.

Abstract

The purpose of this study is to compare the energy consumption and electrical power demand characteristics of a house during the heating and cooling seasons under a variety of heating and cooling modes to determine which mode might yield the best energy alternative under established comfort standards. The study was performed in a contemporary house in California that has unique Heating Ventilating and Air-conditioning (HVAC) features which includes radiant floor heating and cooling, forced-air hydronic heating and cooling, and ventilation at night to reduce air conditioning load by pre-cooling building mass.

Three discrete modes of cooling the home were tested during the cooling modes under similar weather conditions. Comfort levels were measured and determined by percent mean vote (PMV) and predicted percent dissatisfied (PPD) values as per ASHRAE standards. Each cooling mode was tested for approximately one month. The three cooling modes compared against each other are as follows.

4) Mode 1: Conventional forced-air to meet cooling loads in response to a thermostat setting
5) Mode 2: Conventional forced-air combined with hydronic slab precooling,
6) Mode 3: Conventional forced-air combined with night ventilation precooling supplemented as needed with hydronic slab precooling.

Two discrete heating modes were used to compare heating energy consumption during the winter months with each mode tested for approximately one month under similar weather conditions. The two heating modes compared against each other are as follows.

3) Mode H1: Hydronic radiant slab heating
4) Mode H2: Hydronic and forced-air heating

The study shows shifts in energy demand from afternoon to late night, due to slab pre-cooling and slab pre-cooling with night time ventilation, respectively. Fan power accounted for most of the power used in the latter case. During heating under reasonably similar temperature and weather conditions, the energy consumption with hydronic forced-air heating was similar compared against hydronic radiant slab (first floor only) heating, with neither mode exerting an advantage over the other.

Introduction

This study involves a comparison of the energy consumption and electrical power demand characteristics of a house during the heating and cooling seasons. The study is a brief assessment, undertaken in the city of Winters, California during summer of 2002 and the winter months of November through December of 2002 and January through February of 2003. The home is a custom 2484 ft^2 house completed in 2000 located in Winters, approximately 30 miles west of Sacramento, California. The home is shown in Figure 1.

Figure 1Test home front and back views

HVAC System Description

A schematic of the HVAC system is shown in Figure 2 and includes the following:

- **Forced air heating** distribution to all **major rooms** on the first floor and all rooms on the **second floor**, (shown in Figure 3a).
- **Radiant heat** distribution to all **first floor rooms**--the main living area (great room, dining room, kitchen, entry, laundry, and baths) as shown in Figure 3b. The floor is a 3½-in concrete slab poured over ~3-in of rock and 3-in of sand. There is a vapor barrier under the slab and the perimeter is insulated with 2-in of extruded polystyrene to a depth of 16-in below the top of the slab. The radiant tubing is tied to welded wire mesh reinforcement and is from 1 to 2 inches below the surface of the slab.
- Condensing water heater for heating water for domestic and space (radiant and forced-air) heating.
- A split-system HVAC system
    - Condensing unit consists of a refrigerant-to-water heat exchanger capable of delivering chilled water to radiant floor tubing or the hydronic fan coil.
    - Hot/chilled water airhandler equipped with a hydronic coil and variable speed fan.
    - Control system and damper that provides ventilation air using the airhandler fan. Controls allow the occupants to set desired ventilation cooling comfort range.

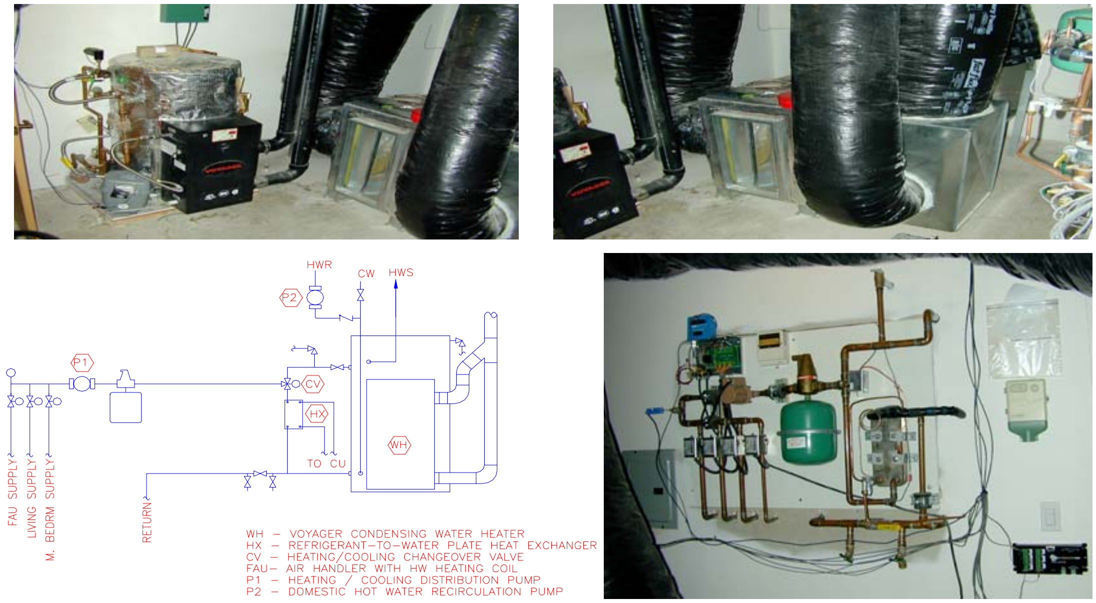

Figure 2 Air Handler, Gas water heater, and Controls

The Great Room, which is a two-story space with a cathedral style ceiling, connects the first and second floors. This results in a thermal connection between the two floors driven by air buoyancy effects. Although the HVAC system has multiple distribution systems, the entire house is controlled as single zone by a thermostat (set to 80°F for cooling mode) located in a second floor bedroom. The owner chose this location because the second floor is not usually occupied during the day. The 80°F for cooling mode setting was selected because it maintains the first floor average temperature of 75°F during the cooling season.

Testing Modes and Methods

<u>Cooling</u>

The system was operated in three modes during the cooling season test period (June-October, 2002). In addition to mechanical cooling, natural ventilation (open windows) was used occasionally. Each operational mode lasted approximately one month, and the cooling modes are defined as:

1. Mode 1, hydronic forced-air (6/21 –7/20): The condensing unit, air handler, and forced-air distribution system were used to meet cooling loads in response to an 80^{o}F thermostat setting.
2. Mode 2, slab pre-cooling and forced-air (7/21-8/20): Conventional cooling and chilled water cooling of the living area concrete floor (first floor) was used to meet cooling load.

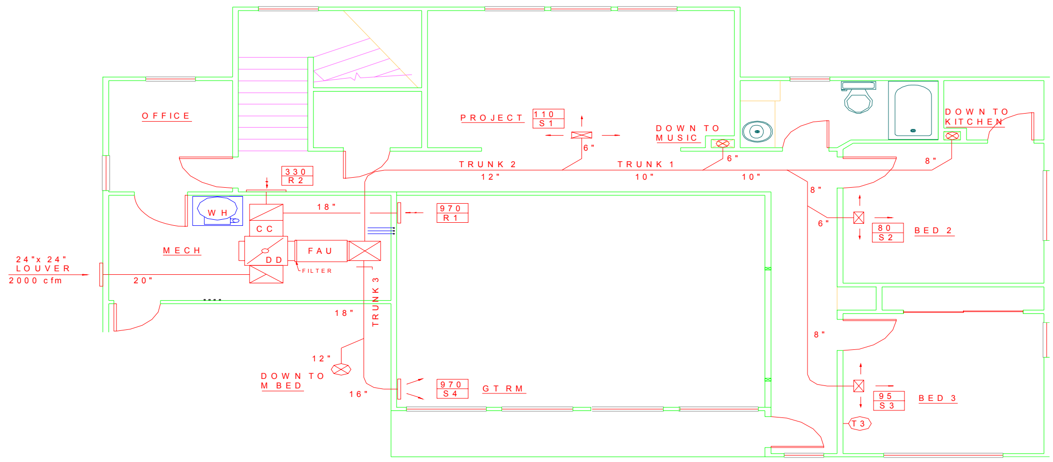

Figure 3a **House floor plan and forced-air distribution system**

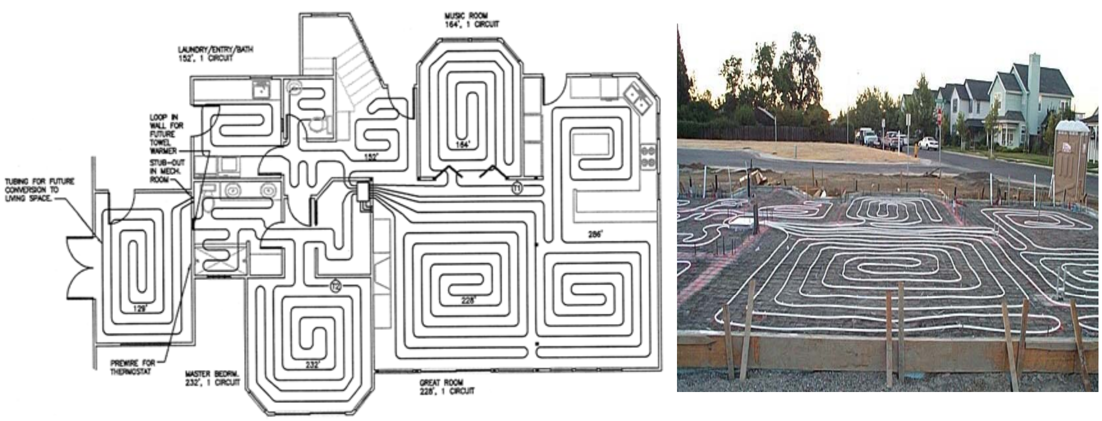

Figure 3b **Home radiant tubing layouts**

Slab cooling was controlled to only occur when indoor temperature failed to drop below 70^{o}F by 4 a.m. Hydronic forced-air cooling operated at all times to maintain the 80^{o}F thermostat setting.

3. Mode 3, slab pre-cooling, forced-air, and night ventilation (8/31-10/7): The controls operated the air handler fan and outside air damper to ventilate the house with outside air when the outside air drops 3^{o}F below the inside air temperature. If the ventilation system failed to lower the indoor air temperature to 70^{o}F by 4 a.m., slab cooling was initiated.

Heading

The system was operated in two modes during the heating season test period (November 2002-February 2003). Each operational mode lasted approximately two months as described below.

1. Mode H1, hydronic floor heating (11/2002 – 12/2002): Water heated with gas is used to condition the living area concrete floor (first floor) to meet the heating load in response to the thermostat settings shown in Table 1.
2. Mode H2, hydronic forced-air heating (1/2003-2/2003): Water heated with gas is delivered to the hydronic fan coil distributing heat via the duct system. Thermostat settings are shown in Table 1.

Table 1 Thermostat Settings

Schedule	**Mode H1 (11/2002 - 12/2002) Thermostat Settings (^oF)**		**Mode H2 (1/2003 – 2/2003) Thermostat Settings (^oF)**	
Weekday	6:45 AM	65	7:00 AM	68
	8:00 AM	62	8:00 AM	62
	2:00 PM	68	3:00 PM	73
	9:00 PM	60	10:00 PM	60
Weekend	9:00 AM	65	9:00 AM	69
	10:00 AM	68	11:00 AM	72
	10:00 PM	60	11:00 PM	63
	Used woodstove, mostly on Friday & Saturday nights. Disabled outside air ventilation.		Downstairs thermostats maintained by radiant heating.	

Monitored Parameters

Parameters monitored to assess the energy performance and verify operational performance are:

- House space conditioning load (heating and cooling) and system status
- Ventilation system cooling output and delivered air conditioning system cooling
- Air conditioning system cooling delivered
- Auxiliary (Fan and pump) electrical energy usage and condensing unit energy use
- Outdoor and indoor conditions (temperatures and relative humidity)

Energy Performance Results (Cooling Season)

Indoor and outdoor environmental conditions during the cooling test period (all three modes) are listed in Table 2. The maximum outdoor temperature was the highest during mode 1 but only by a 0.5^oF than that of mode-2 and 3.4^oF than that of mode-3. There were significantly more hours when the measured hourly-averaged outside temperature was greater than 100^oF during mode 1 than the other modes, but the number of hours that the hourly-averaged temperature ranged between 90 - 100^oF were identical for modes 1 and 2 and slightly higher for mode-3. The averaged outdoor relative humidity was virtually equivalent during mode-1 and mode-2, but mode-3 averaged outdoor relative humidity was roughly 9% less than that in the other modes.

Modes 1 and 2 inside average temperatures and relative humidities are similar; contrasting with mode-3 where indoor temperatures are on average 1.4ºF cooler (night ventilation cooling) and the relative humidity is approximately 9% less than in the other modes. The first floor surface temperature averaged ~72^{o}F for all testing modes, although the sensor may have been located too close to an exterior wall to accurately represent the average floor surface temperature. Figure 4 shows the averaged daily temperature profiles for each test mode. On average, the outside air temperature was highest during mode 1 and lowest during mode 3 test period.

Table 2 Indoor and Outdoor Environment Conditions

	Statistic	**Mode-1**	**Mode-2**	**Mode-3**
$T_{outside}$ (^{o}F)	Maximum	106.0	105.5	102.6
	Average	77.6	75.4	73.3
	Hours: 80 - 90 F	190	164	163
	Hours: 90 - 100 F	93	93	108
	Hours: >= 100 F	24	8	3
$RH_{outside}$ (%)	Maximum	92.2	90.3	89.5
	Average	48.6	49.9	40.3
T_{inside} (^{o}F)	Maximum	83.2	83.3	84.1
	Average	77.4	77.4	76.0
	Minimum	67.6	68.4	66.4
RH_{inside} (%)	Maximum	62.5	60.7	57.0
	Average	51.0	48.8	41.8
	Minimum	22.4	23.2	17.4
T_{floor} (^{o}F)	Maximum	76.2	76.0	74.4
	Average	72.7	72.3	71.1
	Minimum	61.3	66.0	65.0

Figures 5 through 7 illustrate the average demand profile during each mode of operation. The highest hourly-averaged condenser energy use occurred between approximately 2:00 - 8:00 p.m. during mode-1 and mode-2, but practically no fan energy use took place between midnight and 2:00 p.m. during mode-2. The fan and condenser operated throughout the day during mode-1. During mode-3, 15-minute-averaged fan energy usage was the highest between midnight and noon, which nearly balance condenser energy use between 4:00 and 8:00 a.m. and between 2:00 and 8:00 p.m. The condenser energy use between midnight and noon during mode-2 and mode-3 was used to pre-cool the floor slab on the hottest nights when indoor temperatures did not fall below 70ºF by 4 a.m. Figure 8 plots the average demand profile for all three modes. It is clear that average mode-1temporal (8:00 a.m. – midnight) demand is higher than for the other modes. Mode-3 reveals lower on-peak demand and a greater fraction of energy use between midnight and 10:00 a.m. This energy use is primarily from the fan operating to provide ventilation air.

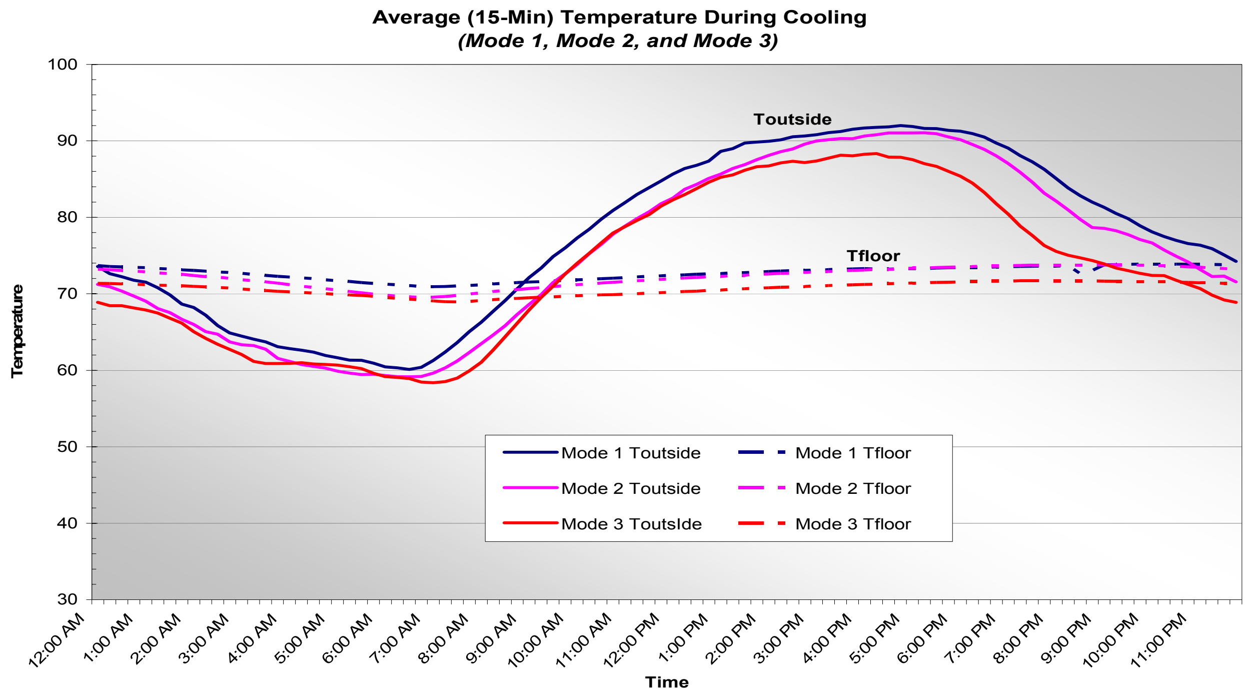

Figure 4 **Hourly averaged temperature profiles during all test periods for inside and outside air and floor slab.**

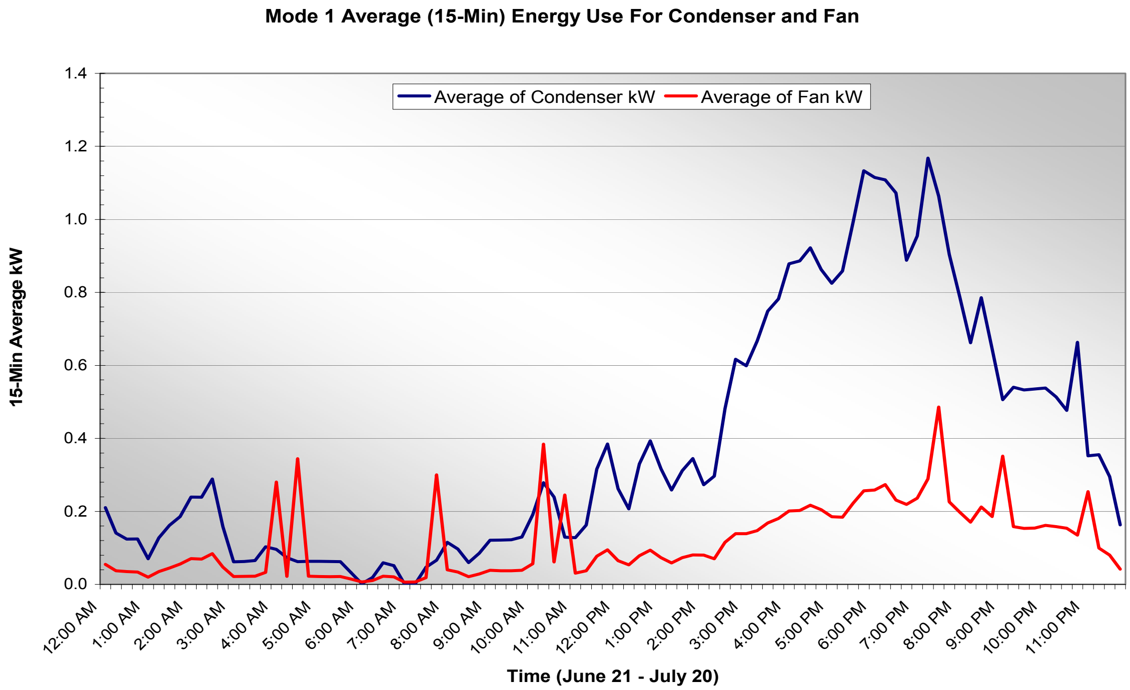

Figure 5 15-min average energy use during test period for condenser and fan (mode –1)

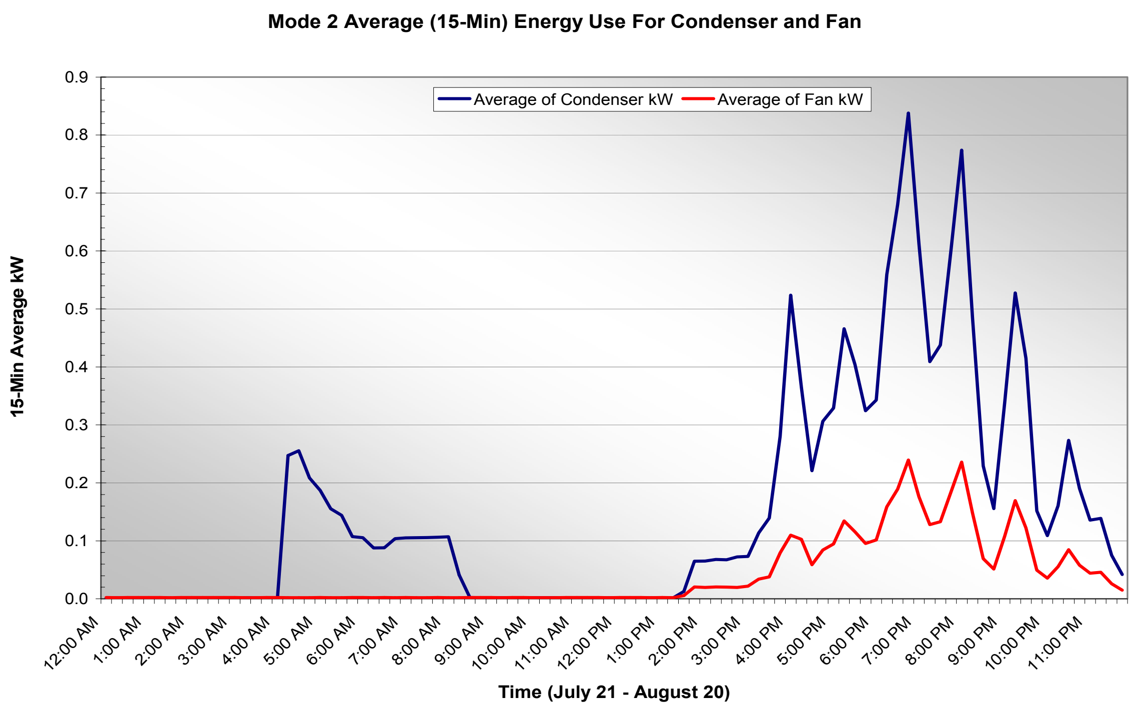

Figure 6 15-min average energy use during test period for condenser and fan (mode-2)

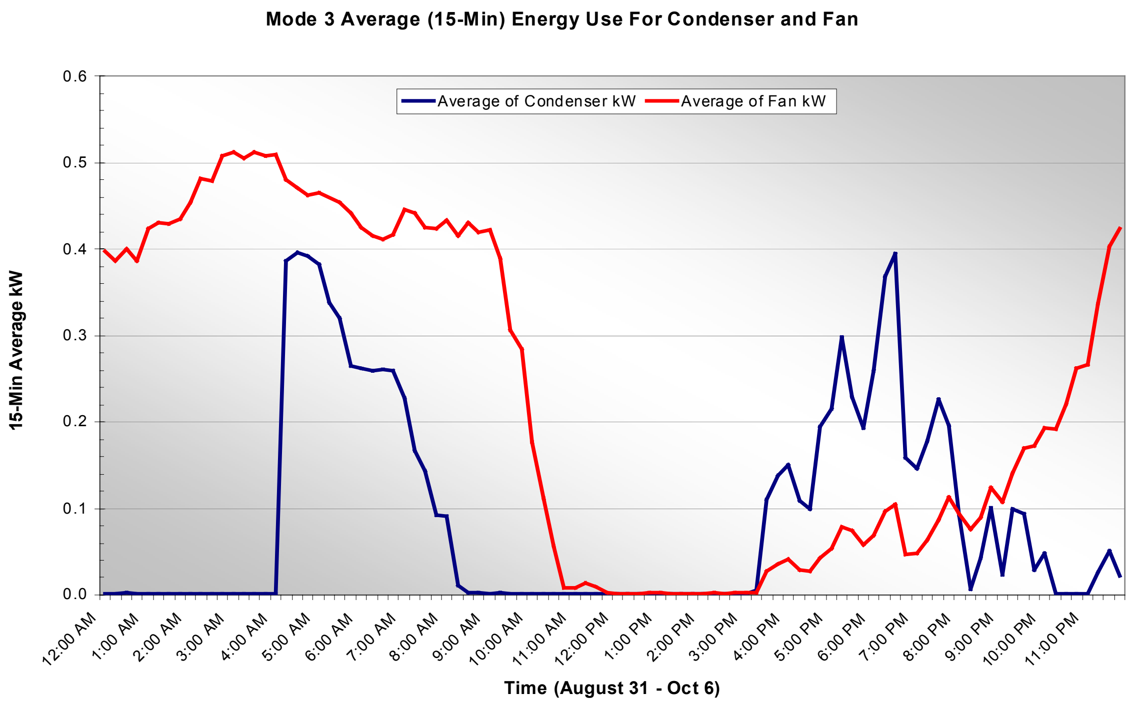

Figure 7 15-min average energy use during test period for condenser and fan (mode-3)

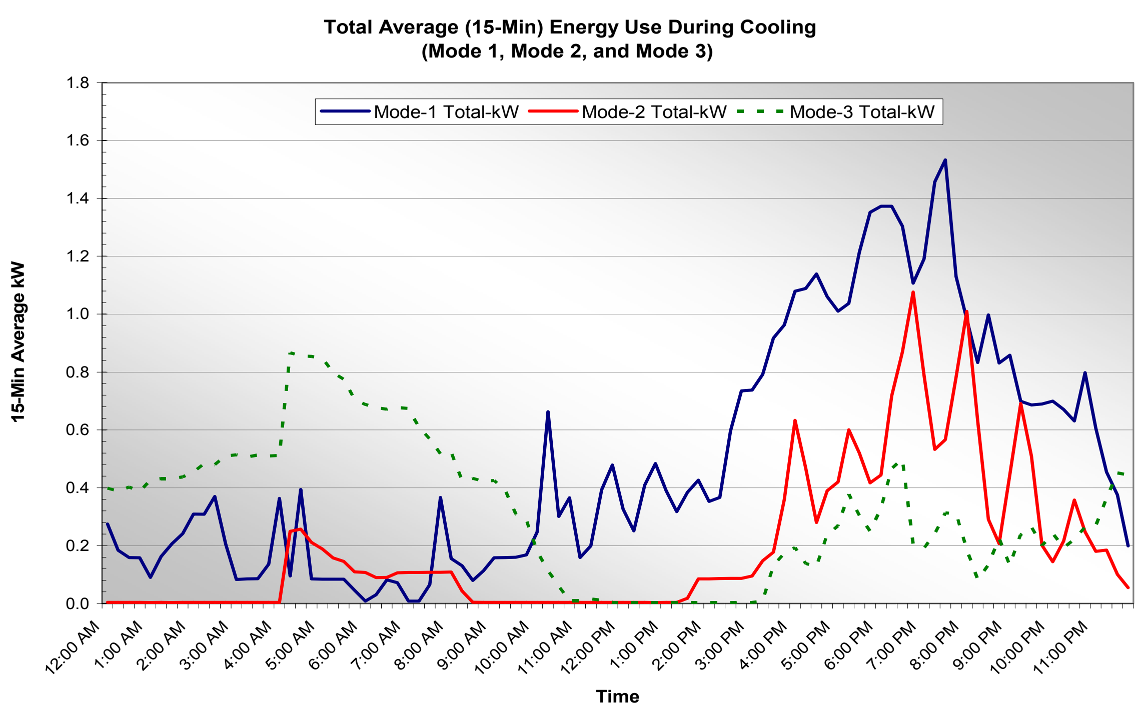

Figure 8 15-min average energy use during all cooling test periods (modes 1, 2, and 3)

The 12 SEER condensing unit has a manufacturer's rated capacity of approximately 24,000 Btu/h and EER of 11, but the capacity rating does not include the condenser unit coupled with the refrigerant-to-water flat-plate heat exchanger. The measured circulating pump wattage was 83 Watts and energy usage is included in the condenser unit energy usage. Table 3 lists the energy performance results achieved during testing for each mode. Mode-1 (hydronic forced-air operation) recorded the highest condenser energy use (mode-3 the lowest), and the highest fan energy use was recorded during mode-3. Overall night ventilation operating "EER" (Btu/Watt-hour) was nearly three times as high as the Mode 1 EER.

Table 3 Cooling Energy Performance Results

Test	*Energy kWh*				*EER (%Difference vs Mode 1)*		
Operation	*Date*	*Condenser*	*Fan*	*Total*	*System*	*Vent*	*Vent + System*
Mode 1	June 21 – July 20	273	83	356	8.7		
Mode 2	July 21 – Aug 20	112	29	141	9.1 (4.5%)		
Mode 3	Aug 31 – Oct 7	80	207	287	9.5 (9.6%)	23.5	19.5 (125.4%)

Energy Performance Results (Heating Season)

Indoor and outdoor environmental conditions during the heating test period are listed in Table 4. The maximum outdoor temperatures were similar for December 2002 through February 2003, but the duration of the higher outdoor temperature was dissimilar for each month. The maximum averaged outside temperature was the highest during November 2002 by approximately 8^{o}F than the other months. The minimum outside air temperatures are very similar throughout the test modes with the lowest air temperature taking place in February. There were significantly more hours in the measured hourly-averaged outside temperature bin of 30 – 40^{o}F during December and February. The numbers of hours in the hourly-averaged temperature bin 40 - 50^{o}F were comparable for months of November and February. All months in the test periods had nearly analogous hours in the temperature range, 50 - 60^{o}F. The horizontal solar gain was virtually non-existent for November, as well as for December and January, but very high for February, implying that the heating load should be lower for February. The first-floor maximum and averaged surface temperature were slightly higher during radiant slab testing mode (mode-H2) but the inside air temperatures were similar throughout the test period. Figure 9 shows the averaged daily temperature profiles for each test month. On average, the outside air temperature profile curves were highest during November and comparable during December and January. December and January were generally overcast due either to frequent storms or extended foggy weather. February was generally clear with warmer days and colder nights.

Table 4 Indoor and Outdoor Environment Conditions

Temperature/Solar Gain	Statistic	Mode H1		Mode H2	
		Nov-02	Dec-02	Jan-03	Feb-03
Outside (^oF)					
	Maximum	77.9	68.0	69.8	70.1
	Average	54.1	48.4	49.6	50.8
	Minimum	34.5	33.8	35.7	28.5
	Hours: 30 - 40 F	30	48	26	60
	Hours: 40 - 50 F	222	391	390	246
	Hours: 50 - 60 F	275	233	262	276
	Hours: > 60 F	192	25	66	88
Horizontal Solar (Btu/hr-ft^2)					
	Maximum	3.0	577.0	590.0	783.0
	Average	0	60.7	64.6	139.2
	Minimum	0	0	0	0
Inside					
	Maximum	79.0	78.6	78.7	80.4
	Average	72.1	70.8	71.3	72.3
	Minimum	65.7	65.4	65.1	66.0
Floor					
	Maximum	69.4	69.2	67.7	67.8
	Average	67.5	66.2	64.7	65.1
	Minimum	64.0	63.5	62.7	62.6

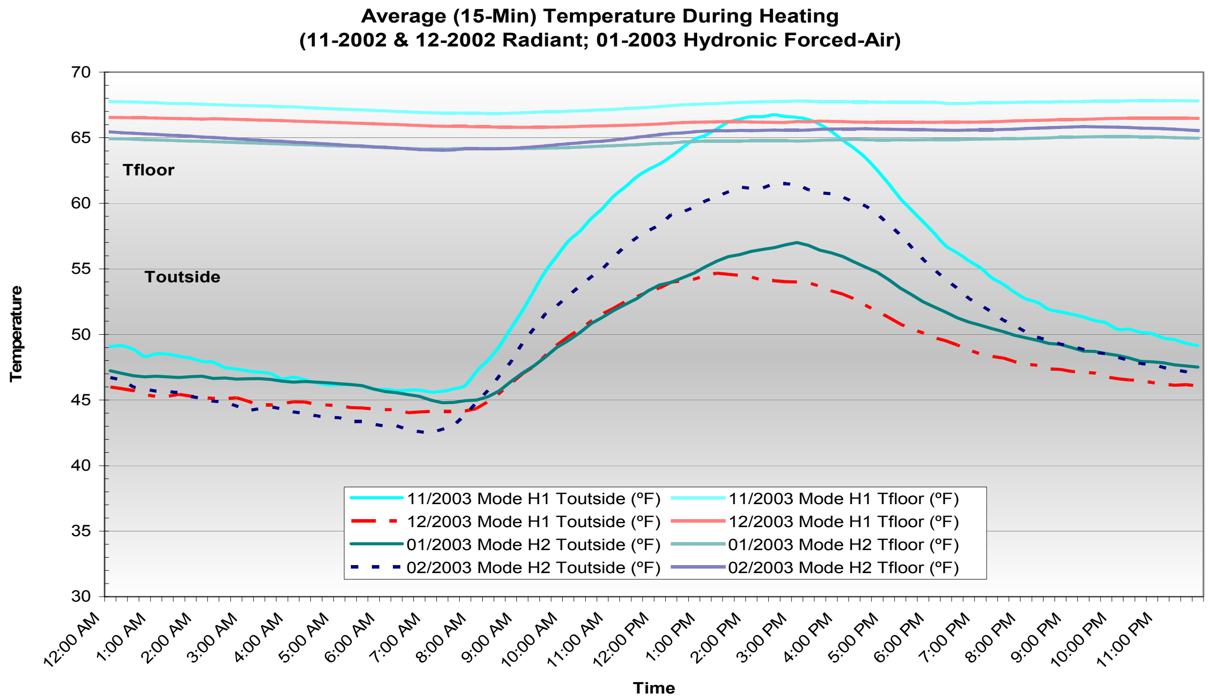

Figure 9 **15-min averaged temperature profiles during 24–hours for outside air and floor slab**

Figure 10 illustrates the energy usage profiles during each month of operation. Both months of mode-H1 testing revealed similar average energy profiles but December had significantly higher demand (averaged) due to colder outdoor temperatures. The profiles for mode-H2 are noticeably different from those of mode-H1. Mode-H2 test period shows two discretely high energy peaks (wakeup and home arrival/dinner); whereas, during mode-H1 test period more sustained increased energy levels occurred around the same time of mode-H2 peaking times. The peaks occurred between approximately 7:00 - 9:00 AM and 3:00 – 6:00 PM during mode-H2. During mode-H1, the major energy use occurs between 7:00 AM and 10 PM without any significant peaks, but during the December, the energy consumption is much higher between 2:30 p.m. – 10:00 p.m. due to the colder outside air temperatures.

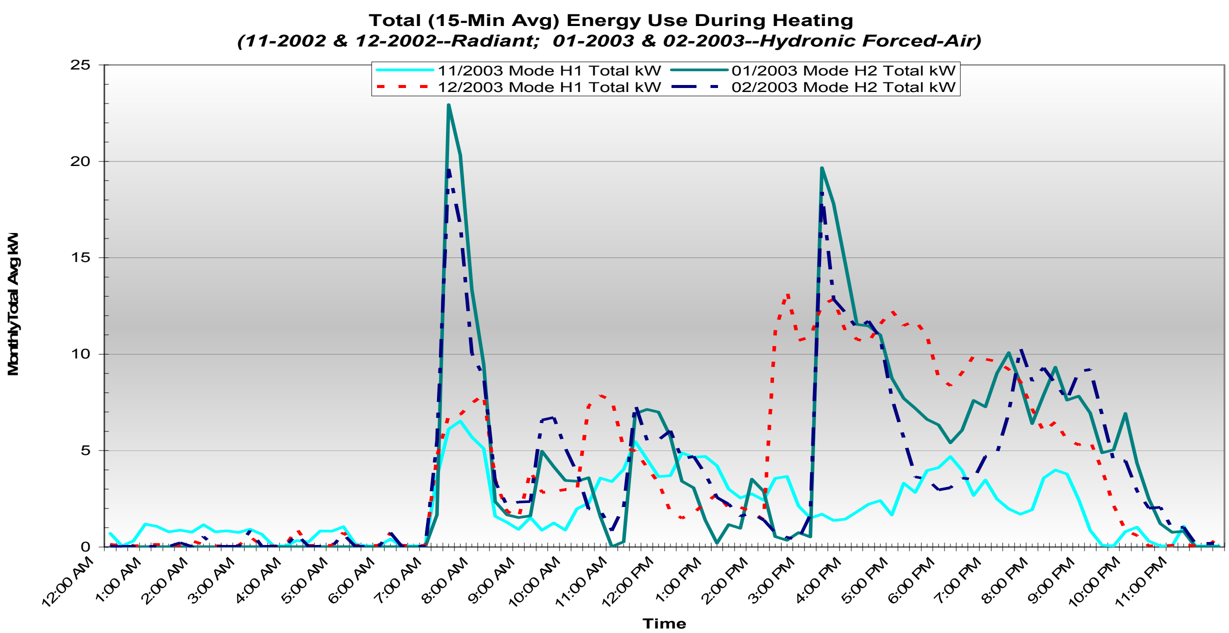

Figure 10 15-min average total energy use for all heating operation modes

Table 5 lists the energy performance results achieved during each testing mode. The gas consumption includes domestic hot water usage, which was assumed to be uniform through modes H1 and H2. During mode-H1 (December) the highest gas and electric energy consumption was recorded in December while the lowest was recorded in November, due to the milder outside air temperatures. During similar outside air temperatures, mode-H1 (December) and mode-H2 (January) total energy consumption are comparable. It should be noted that the measured duct leakage (using the Delta-Q method) was found to be 8.1% of the total air airflow. This is considerably lower than the 25-30% leakage common to new construction. If the Table 5 total energy usage for January were increased by approximately 15-20%, mode-H1 relative performance would be clearly superior.

Table 5 Energy Performance Results

Test	Energy (Btu)	Energy Use (kWh)		
Mode H1 (Radiant)	Gas	Cond + Gas	Fan	Total
Nov-02	2517600	188.4	2.6	191.0
Dec-02	5300950	393.3	5.0	398.3
Mode H2 (Hydronic)				
Jan-03	4314200	351.5	40.1	391.6
Feb-03	4002550	329.4	40.0	369.4

Comfort Evaluation Results

The portable measurement system incorporates thermal comfort standards (ASHRAE 55-1981, ISO 7730 and 7726) in its design. The system is patterned after one developed by Benton et al. (1990) under ASHRAE RP-462, *A Field Measurement System for the Study of Thermal Comfort*. Table 6 presents the test specifications. Thermal comfort measurements were performed for the up and down stairs of the home. The test apparatus consist of a stand with four arm heights on each of its corners (see Table 6 and Figure 11) that contain thermocouples measuring air and globe temperatures and air velocity transducers for measuring the air velocity. The stand was positioned in two to five different locations of each space tested with a total of 32 to 80 sensor measurement locations. A data logger was used to collect and store data that were later entered into a spreadsheet model to compute the comfort indices.

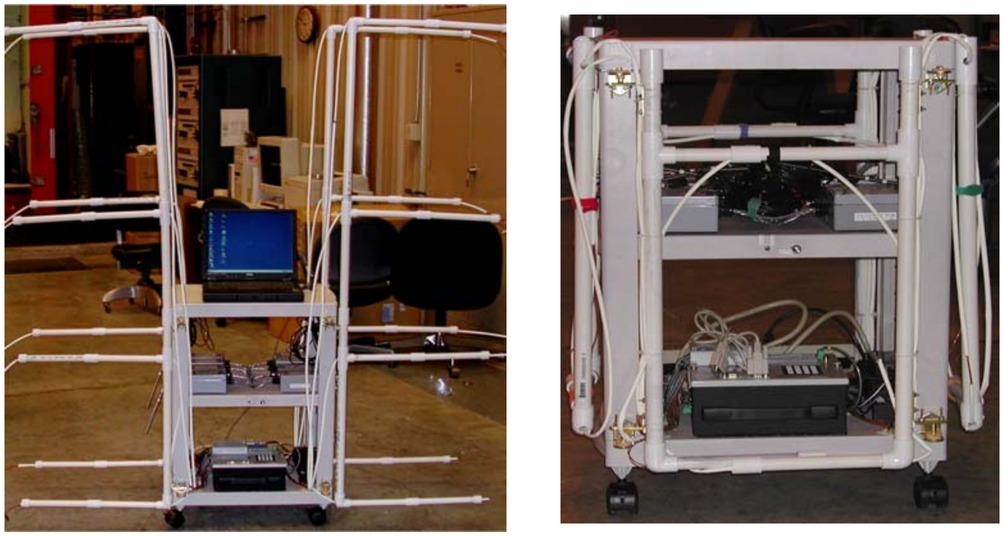

Figure 11 Comfort testing apparatus

To quantify the level of thermal comfort in the test space conditioned, two of the accepted comfort indices for design and field assessment, PMV (predicted mean vote) and PPD (predicted percent dissatisfied), were used. The PMV index predicts the mean response of a large group of people according to the ASHRAE thermal sensation scale. Fanger (1990) developed an equation that related the PMV to imbalance between the heat flow required for optimum comfort at the specified activity and the actual heat flow from the body in a given environment. Fanger also developed a method of relating PPD to the PMV where the criterion for dissatisfied is defined as anyone not voting. Fanger's equations have been incorporated in numerous models developed by others for predicting the PPD and PMV. ISO standard 7730 recommends acceptable PMV limits to be between 0.5 and –0.5 to obtain an 80% comfort level. The PPD assumes thermal neutrality (zero percent) is the optimum condition. The PPD is comparable to the PMV at a PPD less than or equal to 10%. The PMV and PPD were computed from air temperature, mean radiant temperature, relative humidity, air velocity, metabolic rate, and clothing level incorporating most parameters recommended by ASHRAE (1992) and ISO (1985). A spreadsheet program and macros were used to derive time-averaged PMV and PPD values based on a model developed by Int-Hout (1990). Two comfort percentages were derived: one based on the PMV; the other based on the PPD.

Tables 6 through 8 show the comfort rating of the home during mode-2 HVAC system operation for four spaces (living room, master bedroom, and two upstairs bedrooms). For the highest activity level (Cleaning) with both levels of clothing, all spaces where 100% uncomfortable except for the living room at the lower clothing level (clo 0.6, 17.5% are comfortable). The PMV averaged 0.6 to 1.3 indicating the discomfort is due to the space being to warm for this activity.

Table 6 Comfort Rating: Cleaning Activity Level

Activity And Clothing Level		Comfort Rating (%)		Actual Comfort			
		PMV	***PPD***	***PMV***		***PPD (%)***	
(Met 116.7, Clo 1)		(±0.5)	(≤10%)	Range	Averaged	Range	Averaged
	Living Room	0.0	0.0	1 - 1.3	1.2	24.2 - 41.6	33.9
	Master Bedroom	0.0	0.0	1.1 - 1.4	1.3	30 - 44.4	38.2
	Upstairs Bedroom-1	0.0	0.0	1.2 - 1.4	1.3	36.6 - 45.8	41.7
	Upstairs Bedroom-2	0.0	0.0	1.2 - 1.4	1.3	37.5 - 45.2	41.2
(Met 116.7, Clo 0.6)							
	Living Room	17.5	17.5	0.3 - 0.8	0.6	7.5 - 18.1	12.6
	Master Bedroom	0.0	0.0	0.6 - 1.0	0.8	13.3 - 26.6	20.3
	Upstairs Bedroom-1	0.0	0.0	0.8 - 1.0	0.9	18.7 - 27.6	23.4
	Upstairs Bedroom-2	0.0	0.0	0.8 - 1.0	0.9	19.5 - 26.9	23

Changing the activity to standing, a 100% comfortable rating is obtained in the living room at a clo of 1 and in both upstairs bedroom at a clo of 0.6. The lowest comfort rating occurs in the living room at a clo of 0.6. The cases when comfort rating is less than 100% is caused by the space being too cool (clo 1, PMV averaging -0.7 to -0.3) or too warm (clo 0.6, PMV averaging 0.4 to 0.5) as revealed in Table 7.

Table 7 Comfort Rating: Standing Activity Level

Activity And Clothing Level		Comfort Rating (%)		Actual Comfort			
		PMV	***PPD***	***PMV***		***PPD (%)***	
(Met 69, Clo 1)		(+-0.5)	(<=10%)	Range	Averaged	Range	Averaged
	Living Room	100.0	100.0	-0.1 - 0.4	0.2	5.0 - 9.0	6.2
	Master Bedroom	81.3	75.0	0.2 - 0.6	0.4	5.5 - 13.4	8.8
	Upstairs Bedroom-1	43.8	43.8	0.4 - 0.6	0.5	7.7 - 13.5	10.6
	Upstairs Bedroom-2	50.0	31.3	0.4 - 0.6	0.5	8.2 - 12.7	10.3
(Met 69, Clo 0.6)							
	Living Room	21.3	18.8	-1.1 - -0.4	-0.7	7.9 - 29.8	15.1
	Master Bedroom	84.4	81.3	-0.7 - -0.1	-0.4	5.3 - 15.1	8.4
	Upstairs Bedroom-1	100.0	100.0	-0.4 - -0.1	-0.3	5.2 - 9.1	6.5
	Upstairs Bedroom-2	100.0	100.0	-0.4 - -0.1	-0.3	5.4 - 8.2	6.6

A seated activity in the space with a clo of 1 yields a 92.5 to 100% comfort rating for both up and down stairs, but reducing the clo to 0.6 generated 100% discomfort for both floors. The discomfort is due to the space being too cold (PMV averaging -1.3 to -0.8). The higher discomfort ratings occurred during cleaning (clo 1) where the PPD averaged above 33.9% for all spaces. The lower PPD averages (discomfort rating) occurred during the seated (clo 1) activity ranging between 5.4 to 7%.

Table 8 Comfort Rating: Seated Activity Level

Activity And Clothing Level		Comfort Rating (%)		Actual Comfort			
		PMV	*PPD*	*PMV*		*PPD (%)*	
(Met 58, Clo 1)		(+-0.5)	(<=10%)	Range	Averaged	Range	Averaged
	Living Room	93.8	92.5	-0.7 - 0.0	-0.3	5.0 - 14.0	7.0
	Master Bedroom	100.0	100.0	-0.3 - 0.3	0.0	5.0 - 6.8	5.4
	Upstairs Bedroom-1	100.0	100.0	-0.1 - 0.3	0.1	5.0 - 6.7	5.6
	Upstairs Bedroom-2	100.0	100.0	0.0 - 0.2	0.1	5.0 - 6.3	5.4
(Met 58, Clo 0.6)							
	Living Room	0.0	0.0	-1.8 - -1.0	-1.3	24.4 - 68.7	42.0
	Master Bedroom	0.0	0.0	-1.3 - -0.6	-1.0	12.8 - 42.8	24.9
	Upstairs Bedroom-1	0.0	0.0	-1.0 - -0.6	-0.8	13.0 - 27.6	19.0
	Upstairs Bedroom-2	0.0	0.0	-1.0 - -0.7	-0.8	14.2 - 25.3	19.4

During comfort measurements, the averaged air velocity downstairs ranged between 6.0 and 6.8 ft/s when the forced-air fan was not on and from 16.2 to 17.3 ft/s when the fan was on dependent on the sensor location as shown in Table 9. The upstairs velocity averaged between 4.0 and 5.9 ft/s (fan off) and 12.2 and 16.1 ft/s (fan on). When the fan was on, the averaged air velocity downstairs appears to be evenly distributed, but varies within 4 ft/s upstairs. The air velocity is fairly stable when the fan is off up and down stairs. The air temperatures were within 1^{o}F when the fan was off and within 2^{o}F when it was on. The standing height sensor location typically records the highest air temperature, and the lowest is recorded at the ankle sensor location. Typical temperature and velocity profiles showing fluctuations in temperature and velocity during comfort data collection are shown in Figures 12 and 13.

Table 9 Averaged Air Velocity (ft/s) And Temperature (^{o}F)

8/20/2002 HVAC Fan Off								
	V_{ankle}	V_{waist}	V_{head}	$V_{standing}$	T_{ankle}	T_{waist}	T_{head}	$T_{standing}$
Living Room -Afternoon	6.1	6.8	6.0	6.1	68.5	69.3	69.7	70.2
Upstairs -Morning	5.90	4.59	4.03	4.93	67.53	68.06	68.29	68.41
8-21-2002 HVAC Fan On								
	V_{ankle}	V_{waist}	V_{head}	$V_{standing}$	T_{ankle}	T_{waist}	T_{head}	$T_{standing}$
Living Room - Morning	16.5	16.5	17.3	16.2	67.7	68.8	69.2	69.6
Upstairs - Afternoon	12.3	12.2	13.8	16.1	71.6	72.2	72.7	73.0

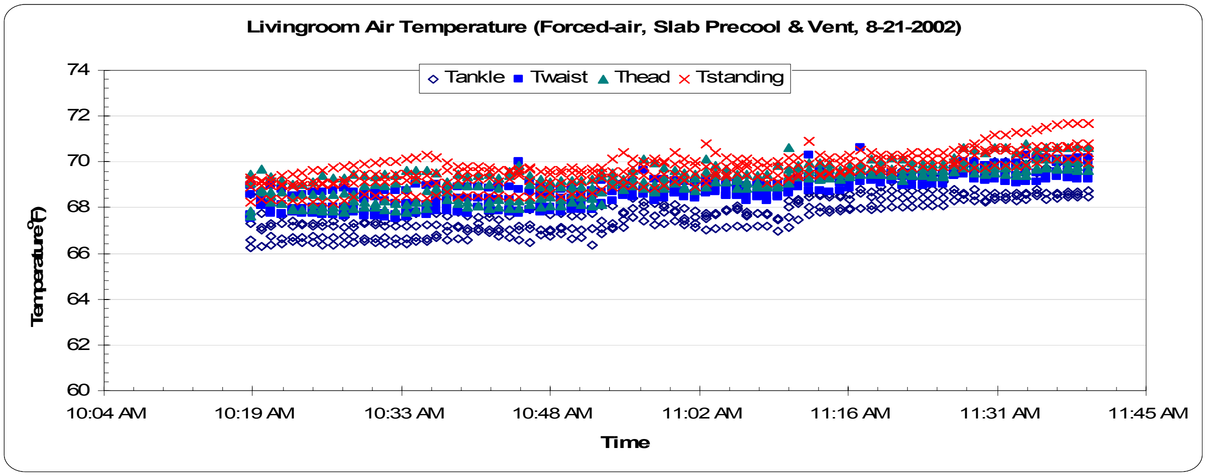

Figure 12 **Sample temperature profile**

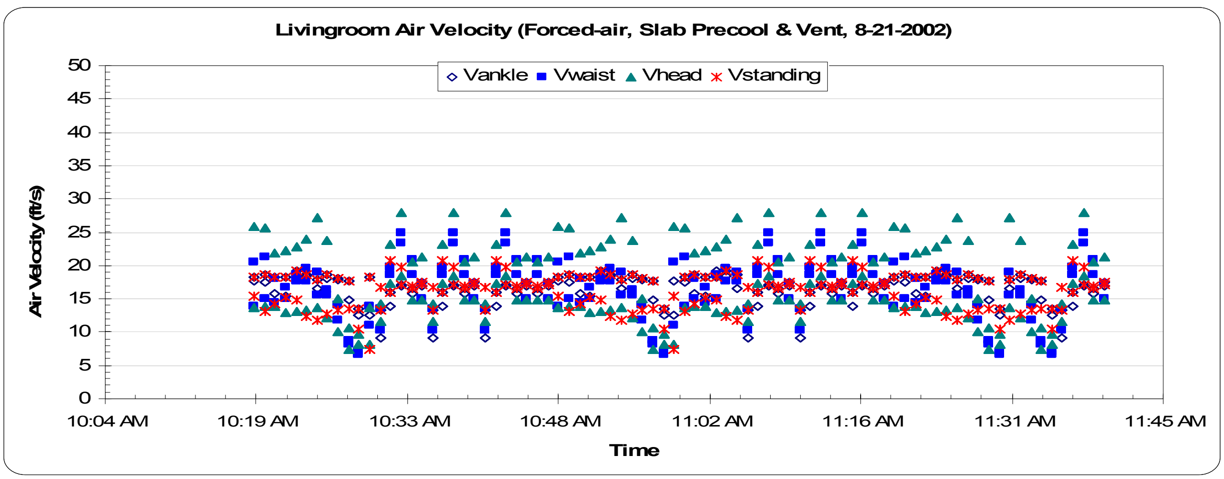

Figure 13 **Sample air velocity profile**

Conclusions

Cooling performance results reveal that slab pre-cooling caused some of the energy demand to shift from the on-peak periods (2 to 8 PM) to early morning off-peak periods (4 to 8 AM). This is due to the ability of the slab cooling to reduce on-peak cooling loads. Coupling slab pre-cooling with nighttime ventilation significantly shifts the energy demand profile from primarily in the afternoon to the nighttime with most of the off-peak load coming from the fan. The combined benefits of slab pre-cooling and nighttime ventilation significantly increase system overall performance and contributes to an "inverted" demand profile relative to mode 1 operation.

Heating performance results indicate approximate equivalence for the hydronic forced-air heating mode relative to the radiant floor heating mode during similar outside environment conditions. The low duct leakage (8% of system airflow) affected the result because a more typical "leaky" duct system would result in a performance advantage for the radiant floor heating.

While seated with lightweight clothing the home was uncomfortable—to cool, but while cleaning with the same clothing level the home was uncomfortable—to warm. With slightly heavier weight clothing the home is comfortable when seated and standing. Since the averaged inside temperature was lower during the test period than the monthly average, the home should be comfortable the majority of the time even with lightweight clothing when seated or standing.

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